

Gamma-ray emission from nova outbursts

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Abstract.

Classical novae produce radioactive nuclei which are emitters of gamma-rays in the MeV range. Some examples are the lines at 478 and 1275 keV (from ^7Be and ^{22}Na) and the positron-electron annihilation emission, with the 511 keV line and a continuum. Gamma-ray spectra and light curves are potential unique tools to trace the corresponding isotopes and to give insights on the properties of the expanding envelope. Another possible origin of gamma-rays is the acceleration of particles up to very high energies, so that either neutral pions or inverse Compton processes produce gamma-rays of energies larger than 100 MeV. MeV photons during nova explosions have not been detected yet, although several attempts have been made in the last decades; on the other hand, GeV photons from novae have been detected with the Fermi satellite in V407 Cyg, a nova in a symbiotic binary, where the companion is a red giant with a wind, instead of a main sequence star as in the cataclysmic variables hosting classical novae. Two more novae have been detected recently (summer 2012) by Fermi, apparently in non symbiotic binaries, thus challenging our understanding of the emission mechanism. Both scenarios (radioactivities and acceleration) of gamma-ray production in novae are discussed.

1. Introduction

The γ -rays are the most energetic photons in the Universe, revealing very energetic phenomena, like the explosions of accreting white dwarfs in binary systems as classical or recurrent novae. Two types of γ -ray emission are expected from novae. First, γ -rays are emitted because radioactive nuclei are synthesized and ejected as a consequence of the explosion. Such emission occurs in the MeV energy domain (see Table 1), and it traces nucleosynthesis directly. It has never been detected, neither with CGRO/Comptel (Iyudin et al. 1995) nor with other previous satellites or the current INTEGRAL. A second possible origin of γ -rays is related to particle acceleration in strong shocks between nova ejecta and circumstellar material; this is particularly feasible when there's a red giant companion (i.e., in the symbiotic recurrent nova case), because nova ejecta shocks the red giant wind. But it could also occur whenever there is dense enough circumstellar matter to favor shocks. Two processes can explain the emission of VHE (very high energy) gamma-rays, with E larger than 100 MeV (i.e., in the GeV range): inverse Compton effect or neutral pion decay (see next section for details). This kind of emission has been detected already in three novae by the LAT instrument onboard the Fermi satellite (Cheung 2013).

2. “Fermi or GeV novae”: Very High Energy (VHE) γ -rays ($E > 100$ MeV)

The first nova detected in VHE γ -rays was V407 Cyg (Abdo et al. 2010). This source is a binary system with a white dwarf and a Mira pulsating red giant companion. In March 2010 a nova outburst was detected from V407 Cyg. The Fermi/LAT telescope discovered a VHE γ -ray source (photons with $E > 100$ MeV) which was coincident in position with V407 Cyg. As shown in Fig. 1 of Abdo et al. (2010), such emission lasted for about two weeks after the nova eruption. It was not completely clear if the emission was originated by neutral pion decay or inverse Compton, the first corresponding to the hadronic scenario (accelerated protons are responsible) and the second one to the leptonic one (accelerated electrons are responsible). A detailed analysis presented in Martin & Dubus (2013), favored the leptonic scenario, where accelerated electrons upscatter (Inverse Compton) nova light up to very high energies.

Before V407 Cyg was detected by Fermi/LAT, a theoretical prediction of particle acceleration during the 2006 eruption of the recurrent symbiotic nova RS Oph was made by Tatischeff & Hernanz (2007), as well as its ensuing VHE γ -ray emission (Hernanz & Tatischeff 2012). The previous eruption of this nova was in 1985, so the recurrence period is 21 years. A self consistent thermonuclear runaway model for this nova is not easy to find, because a combination of high accretion rate (at least $2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$) and extremely large initial mass of the white dwarf (at least $1.35 M_{\odot}$) is required (Hernanz & José 2008). When the nova explodes, an expanding shock wave sweeps the red giant wind, and the system behaves as a “miniature” supernova remnant, much dimmer and evolving much faster.

The evolution of the blast wave of RS Oph (2006 outburst) is shown in Figure 1 from Tatischeff & Hernanz (2007), where the time dependence of the forward shock velocity as deduced from IR spectroscopic observations is compared to that from the X-ray observations with RXTE. Two caveats are, first why the cooling phase started as early as 6 days, when $T(\text{shock})$ was about 10^8 K and thus radiative cooling was not important, and second why shock velocities derived from X-rays are lower than those from IR measurements. The answer is that there was particle acceleration (i.e., generation of cosmic rays), with the ensuing energy loss (associated with particle escape). Such losses were much more efficient (more than 100 times larger) than radiative losses to cool the shock, explaining the very fast cooling. They also explain the lower shock velocity deduced from X-ray observations, because the usual relation for a test-particle strong shock underestimates the shock velocity when particle acceleration is efficient, because the shock temperature is lower (see Tatischeff & Hernanz (2007)).

A prediction of the γ -ray emission associated to the accelerated particles was made (Hernanz & Tatischeff 2012). The production of neutral pions (π^0) was calculated from the density in the red giant wind and the cosmic-ray energy density required to explain the IR and X-ray observations. The Inverse Compton (IC) contribution was estimated from the non thermal synchrotron luminosity (deduced from the early radio detections of RS Oph at frequencies below 1.4 GHz by Kantharia et al. (2007)). Pion decay dominates over inverse Compton in RS Oph, but this should not be the general rule for all novae in symbiotic binaries. Comparison between theoretical predictions for RS Oph and Fermi/LAT sensitivities shows that RS Oph would have been detected by Fermi/LAT, if it had been in orbit in 2006.

In addition to V407 Cyg, two more novae - Nova Sco 2012 and Nova Mon 2012 - have also been detected by Fermi/LAT at $E > 100$ MeV. However, the companions of these exploding white dwarfs are not red giants, so the scenario is different, although

a dense circumstellar environment (“playing the role” of the missing red giant wind) exists, at least for Nova Mon 2012, which in fact was first discovered in γ -rays than optically (see Shore et al. (2013) for details about this nova).

3. γ -rays from radioactivities: $E \sim 1$ MeV

The potential role of novae as γ -ray emitters was already pointed out in the 70’s (Clayton & Hoyle 1974) and 80’s (Clayton 1981); see recent review in Hernanz (2008). The γ -ray signatures of classical novae depend on their yields of radioactive nuclei. CO and ONe novae differ in their production of ^7Be and ^{22}Na , whereas they synthesize similar amounts of ^{13}N and ^{18}F . Thus CO novae should display line emission at 478 keV related to ^7Be decay, whereas for ONe novae line emission at 1275 keV related to ^{22}Na decay is expected. In both nova types, there should be as well line emission at 511 keV related to e^-e^+ annihilation, and a continuum produced by Comptonized 511 keV emission and positronium decay. In Table 1 the main properties of the radioactive nuclei synthesized in novae are shown.

All the results presented in this paper correspond to the most recent nucleosynthetic yields (J. José, unpublished) of nova models computed with the SHIVA code, described in José & Hernanz (1998), and the nuclear reaction rates from Iliadis et al. The most significant change is the reduction of the amount of ^{18}F , in the last years, because of revised rates of the nuclear reactions affecting its production and destruction (as reported in Hernanz et al. (1999); Coc et al. (2000); De Séréville et al. (2003); Chafa et al. (2005), and others).

The shape and intensity of the γ -ray output of novae as well as its temporal evolution, depend on the amount of γ -ray photons produced and on how they propagate through the expanding envelope and ejecta (Leising & Clayton 1987; Gómez-Gomar et al. 1998). Interaction processes affect the propagation of photons, i.e. Compton scattering, e^-e^+ pairs production and photoelectric absorption.

A Monte Carlo code, based on the method described by Pozdniakov, Sobolev & Sunyaev (1983) and Ambawani & Sutherland (1988), was developed by Gómez-Gomar et al. (1998) to compute the γ -ray output of novae. The temporal evolution of the whole γ -ray spectrum of some representative models is shown in Figure 1. The most prominent features are the annihilation line at 511 keV and the continuum at energies between 20-30 keV and 511 keV (in both nova types), the ^7Be line at 478 keV in CO novae, and the ^{22}Na line at 1275 keV in ONe novae.

The light curves of the 478 keV line are shown in Figure 2: the flux reaches its maximum ($\sim 10^{-6}\text{phot cm}^{-2}\text{ s}^{-1}$, for $d=1\text{kpc}$) at day ~ 5 in the model with mass $1.15 M_\odot$. The width of the line is ~ 8 keV. There is a previous maximum, which has nothing to do with the envelope’s content of ^7Be , but with the strong continuum related to the annihilation of ^{13}N and ^{18}F positrons.

The ^{22}Na line at 1275 keV appears only in ONe novae, because CO novae do not synthesize this isotope. The rise phase of the 1275 keV line light curves lasts between 10 ($1.25 M_\odot$) and 20 days ($1.15 M_\odot$). After the maximum (flux $\sim 10^{-5}\text{phot cm}^{-2}\text{ s}^{-1}$ at $d=1\text{kpc}$), the line reaches the stable decline phase dictated by the lifetime of ^{22}Na , 3.75 years; during this phase, the line intensities directly reflect the amount of ^{22}Na ejected mass (see Figure 2). The width of the line is around 20 keV, which is a problem for its detectability with instruments having good spectral resolution, which are best suited for narrow lines (e.g., Ge detectors of SPI on board INTEGRAL).

The early γ -ray emission of novae is related to the disintegration of the very short-lived β^+ -unstable isotopes ^{13}N and ^{18}F . The radiation is emitted as a line at 511 keV plus a continuum related with both the positronium continuum and the Comptonization of the photons emitted in the line. The sharp cut-off at energies 20-30 keV is caused by photoelectric absorption. The light curves of the 511 keV line are shown in Figure 3 for a CO and an ONe novae. Larger fluxes are emitted in the continuum (e.g., in Figure 4 are shown the light curves for various continuum bands appropriate for Swift/BAT). The two maxima in the light curves correspond to ^{13}N and ^{18}F decays, but the first maximum is difficult to resolve because its duration is really short; in addition, it is very model dependent: only ^{13}N in the outermost zones of the envelope can be seen in γ -rays because of limited transparency at very early epochs and, therefore, the intensity of the first maximum depends on the efficiency of convection. This first maximum gives thus an important insight into the dynamics of the envelope after peak temperature is attained at its base.

The annihilation emission is the most intense γ -ray feature expected from novae, but unfortunately it has a very short duration, because of the short lifetime of the main positron producers (^{13}N and ^{18}F). There are also positrons available from ^{22}Na decay in ONe novae, but these contribute much less (they are responsible for the *plateau* at a low level, between 10^{-6} and 10^{-5} phot cm $^{-2}$ s $^{-1}$ for $d=1\text{kpc}$; see Figure 3). These positrons do not contribute all the time, because after roughly one week the envelope is so transparent that ^{22}Na positrons escape freely without annihilating. In summary, annihilation radiation lasts only ~ 1 day at a high level, and one to two weeks at a lower level *plateau* (the latter mainly in ONe novae, but also at a very much lower level in CO ones, which have a ~ 1000 times smaller amount of ^{22}Na ,).

An important fact is that annihilation radiation is emitted well before the visual maximum of the nova, i.e. before the nova is discovered optically. This early appearance of γ -rays from electron-positron annihilation makes their detection through pointed observations almost impossible. Only wide field of view instruments, monitoring continuously the sky in the appropriate energy range can detect it. A detailed study has been performed with the Burst Alert Telescope (BAT) onboard the Swift satellite (Senziani et al. 2008). Swift/BAT offers an interesting opportunity to search for annihilation emission, because of its huge field of view, good sensitivity, and well-suited energy band (14-200 keV). Data from Swift/BAT can be retrospectively analyzed to search for prompt γ -ray emission from the direction of novae after their optical discovery. The search for emission from the 24 classical novae discovered since the Swift launch yielded no positive results, which was understood since none of them was close enough. Other previous searches were made with the TGRS instrument onboard the Wind satellite (Harris et al. 1999), and the BATSE instrument onboard the CGRO satellite (Hernanz et al. 2000).

4. Summary and conclusions

The long awaited detection of γ -rays from novae has been accomplished with the Fermi/LAT (Abdo et al. 2010); this instrument observed emission of VHE γ -rays, produced either by neutral pions or by inverse Compton, as a consequence of particle acceleration in the shock wave from the interaction between the nova ejecta and the red giant wind in V407 Cyg (or with other circumstellar material in N Sco 2012 and N Mon 2012) . RS Oph, a recurrent nova in a symbiotic binary, i.e., with a red giant com-

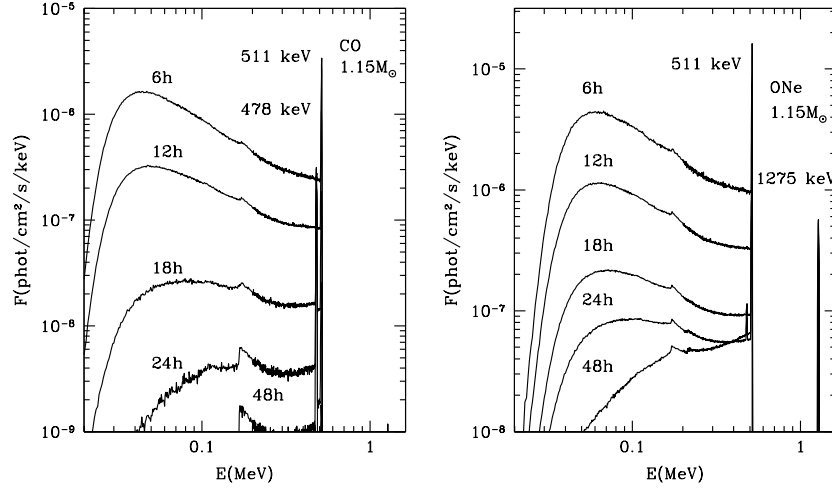


Figure 1. Left panel: Spectra of a CO nova of mass $1.15 M_{\odot}$ at different epochs after T_{peak} ; Right panel: Same for an ONe novae of the same mass.

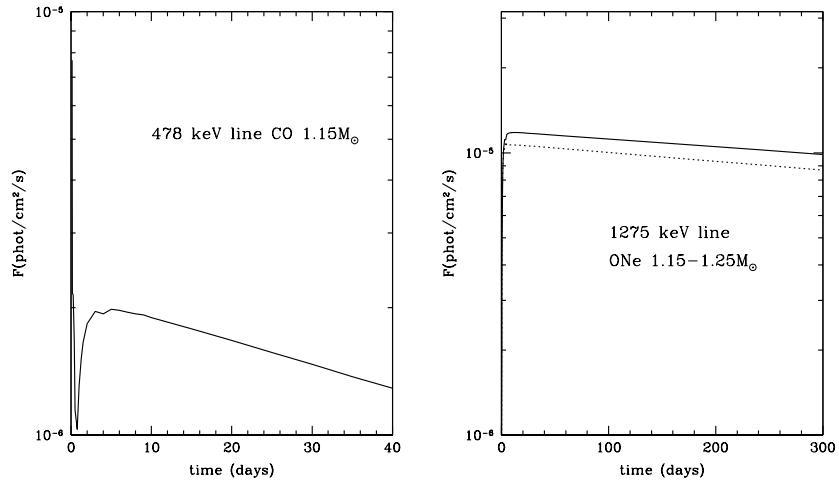


Figure 2. Left panel: Light curve of the 478 keV line for a CO nova with mass $1.15 M_{\odot}$. Right panel: Light curve of the 1275 keV line for ONe novae of 1.15 and $1.25 M_{\odot}$ (solid and dotted, respectively).

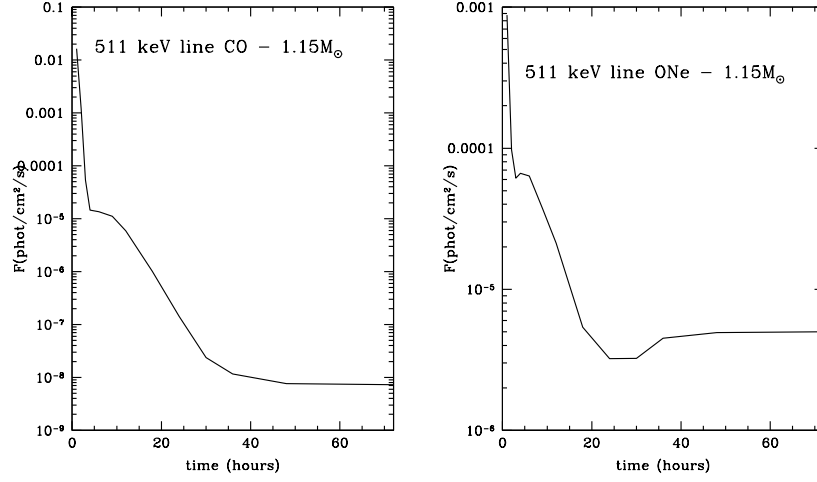


Figure 3. Left panel: Light curve of the 511 keV line for a CO nova with mass $1.15 M_{\odot}$. Right panel: Same for an ONe nova of $1.15 M_{\odot}$.

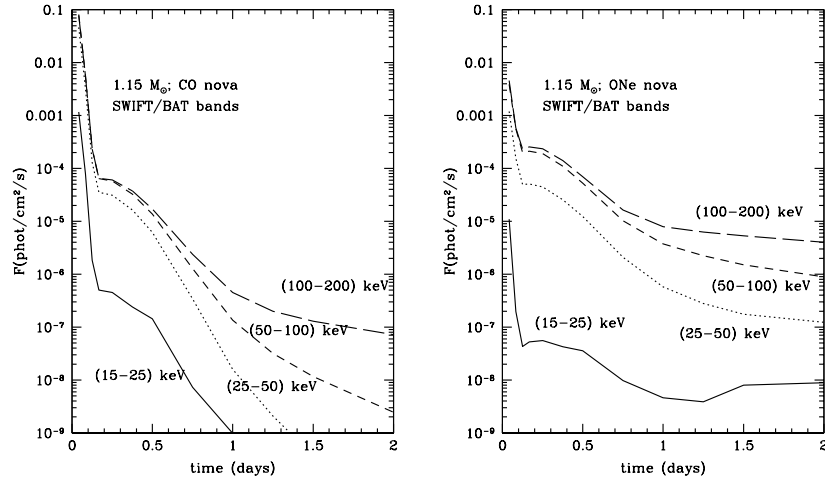


Figure 4. Light curves for various continuum bands appropriate for the Swift/BAT instrument. Left panel: CO nova with mass $1.15 M_{\odot}$. Right panel: Same for an ONe nova of $1.15 M_{\odot}$.

Table 1. Main radioactive nuclei synthesized in nova explosions.

Isotope	Lifetime	Main disintegration process	Type of emission	Nova type
^{13}N	862 s	β^+ -decay	511 keV line and continuum	CO and ONe
^{18}F	158 min	β^+ -decay	511 keV line and continuum	CO and ONe
^7Be	77 days	e^- -capture	478 keV line	CO
^{22}Na	3.75 years	β^+ -decay	1275 and 511 keV lines	ONe
^{26}Al	10^6 years	β^+ -decay	1809 and 511 keV lines	ONe

panion, had already been predicted to emit such VHE photons (Tatischeff & Hernanz 2007).

On the contrary, the detection of γ -rays in the MeV range, from nova radioactivities, has not been achieved yet. The predictions for the current INTEGRAL/SPI instrument are not very optimistic: distances shorter than 0.5 kpc for the ^7Be line at 478 keV, and shorter than 1 kpc for the ^{22}Na line at 1275 keV, are required. A future generation of instruments is needed, either a powerful Compton Telescope (e.g., the ACT project) or a γ -ray lens - Gamma-Ray Imager, GRI - or a combination of both, DUAL (see e.g. Boggs et al. (2004) and von Ballmoos et al. (2012)). The Laue γ -ray lens provides up to now the best perspectives for detecting lines in the MeV range, since a large collecting area (the diffracting crystals acting as a photon concentrator) is combined with a small detector in its focal plane, thus yielding a good signal to noise ratio, not easily reachable with Compton Telescopes. We should wait several years until this already proven concept is feasible for a space mission.

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